

On the Origin of the “Ridge” phenomenon induced by Jets in Heavy Ion Collisions

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We argue that “ridge” in 2-particle correlation function associated with hard trigger at RHIC heavy ion collisions is naturally explained by an interrelation of jet quenching and hydrodynamical transverse flow. The excess particles forming the ridge are produced by QCD bremsstrahlung along the beam (and thus have wide rapidity distribution) and then boosted by transverse flow. Nontrivial correlation between directions of the jet and the radial flow is provided by jet quenching: our straightforward and basically parameter-independent calculation reproduces the angular shape, width and other properties of the “ridge”.

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I. INTRODUCTION

Two most important discoveries made in first years of heavy ion collision experiments at RHIC are (i) robust radial and elliptic flows which are well described hydrodynamically [1], and (ii) strong jet quenching. In the last years one of the hot subjects became an interaction between jets and the medium. Strong modification of the away-side jets seem to be well described by another hydrodynamical “conical flow” [2].

This paper is about another phenomenon observed in jet-related 2-particles correlations, known as “ridge” and found by STAR collaboration. It was originally observed in fluctuation analysis [3] revealing “mini-jets”, and then related to few-GeV jets, for recent summary see e.g. [4]. Its main features are: (i) a peak at relative azimuthal angle $\phi = \phi_1 - \phi_2 = 0$ with a width of about 1 radian, about twice that of the jet; (ii) wide distribution in (pseudo)rapidity η ; (iii) a spectrum of secondaries slightly harder than a bulk one but much softer than that for a jet; (iv) a composition very different from jets, in particular large fraction of baryons/anti-baryons.

We would not go into a review of various ideas proposed to explain the “ridge”. We just report our calculations aimed at testing one specific idea, originating from the paper of S.Voloshin [5], who pointed out that one can get information about the location of the hard collision point by correlating its with the transverse flow. To our knowledge, the present paper is the first attempt to make quantitative estimates based on it, with results we consider very encouraging.

II. ANGULAR CORRELATION BETWEEN JET AND FLOW

As it is well known, radiative QCD processes lead to production of four cones of radiations. Two of them – the “jets” – are better known and studied, since two others produced along the beams. While they are similar in multiplicity and other features to two “jets” (because

appearance and disappearance of the same color current produces similar radiation), the hadrons originating from them cannot be separated from “bulk” multiple production in pp collisions. Indeed, they have similarly wide rapidity distribution, and similar transverse momenta p_t in respect to the beam direction, so their presence may only be seen via overall multiplicity increase in jet-containing events, relative to “soft” ones.

In heavy ion collisions the situation is different: as we show below, the “longitudinal cone” products can be naturally separated from the “bulk”. The reason for that is their specific production locations in the transverse plane – the gray circle in Fig.1(a) – which tend to be closer to the nuclear edge than to the center, due to jet quenching. Collective transverse flow boost them strongly in the radial direction, making their azimuthal directions to be well aligned along \vec{r} (especially if one select the right window of $p_t \sim 2 \text{ GeV}$, see below). The next step, explaining why this effect is observable, is a correlation between the radial direction and that of the triggered jet.

The geometry of the phenomenon and the notations used is explained in Fig.1(a), depicting transverse plane at the moment of a collision. For simplicity we discuss only central collisions, for which there is perfect axial symmetry and the elliptic flow is absent. The point at which hard collision takes place is denoted by \vec{r} and the (azimuthal) angle at which triggered jet is emitted is called ϕ_1 . At the moment of production obviously there is no correlation between directions of \vec{r} and ϕ_1 . However this correlation appears for *observed* jets due to jet quenching phenomenon. Indeed, in order to be detected jet has to go through matter a distance (depicted L at the figure) at which quenching takes place, the probability of which we call $P_{\text{quench}}(L)$. Since obviously the distance depends on both r, ϕ_1 and the nuclear radius R

$$L(r, \phi_1) = \sqrt{R^2 - r^2 \sin^2(\phi_1)} - r \cos(\phi_1) \quad (1)$$

this generates the correlation between them to be explored.

Since it is the main point of the phenomenon, let us discuss it in detail. If a jet is produced at small r close to

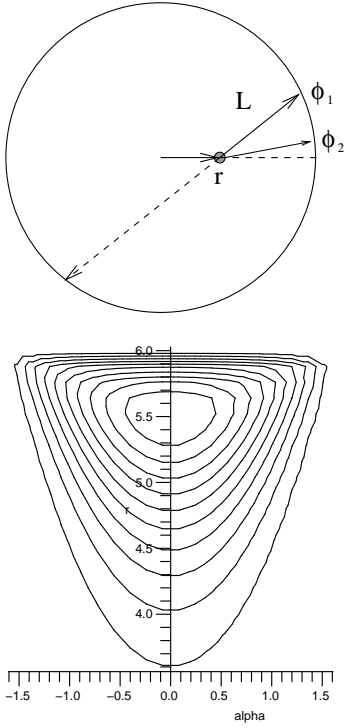


FIG. 1: (a) Schematic view of the transverse plane for central heavy ion collisions. The small circle at coordinate \vec{r} is the place where hard collision takes place, in which a pair of jets (triggered one shown by a solid line, unobserved by the dashed one) are produced. The distance traveled by the triggered jet inside the nucleus is L , which depends on \vec{r} and jet direction angle ϕ_1 . (b) Distribution in $r - \phi_1$ plane.

the nuclear center (where the probability of production $P_{prod}(r)$ has obviously its maximum) there is no correlation, since L in this case is about the same $\approx R$ in all directions. If the jet is produced near the nuclear surface $R - r \ll R$ there is some angular correlation, but a weak one: in this case jet may be emitted in the whole half-plane $-\pi/2 < \phi_1 < \pi/2$. The correlation reducing ϕ_1 distribution to more narrow peak appears only when jets originate at a certain depth inside the nuclei: and the question to be addressed is whether it is strong enough to explain the observed effect.

Although we have used different variants of distributions in the study, it is found to be enough to use the simplest models of the production/quenching, as the results are found to be insensitive to any details. For central collisions of two homogeneous balls of radius R , with a sharp edge, at position r one has collision of two columns of matter with a length $\sqrt{R^2 - r^2}$, and thus “collision scaling” means

$$P_{prod}(r) \sim (R^2 - r^2) \quad (2)$$

The probability of quenching can be written as a simple

exponential damping with distance

$$P_{quench}(L) \sim \exp\left(-\frac{L(r, \phi_1)}{l_{abs}}\right) \quad (3)$$

where l_{abs} is the quenching length. The resulting distribution $P_{prod}P_{quench}$ in $r - \phi_1$ plane is shown in Fig.1(b): one can see that for $r = 4 - 5 fm$ the width of ϕ_1 distribution is about one radian. This width would eventually become the observed width of the “ridge”, as will show below.

The next step in the calculation is to address the effect of the radial flow on spectra of secondaries. As usual, those are determined from Boltzmann thermal distribution at kinetic freezeout temperature T_f , boosted by the flow velocity to

$$\frac{dN}{dy dp_t^2} \sim \exp\left(-\frac{u_\mu p_\mu}{T_f}\right) \quad (4)$$

Here the nonzero components of the flow velocity are written as $u_0 = 1/\sqrt{1 - v^2}$, $u_r = v/\sqrt{1 - v^2}$ (because we focus on the transverse flow). Since we need anisotropy, we can focus on the second term in the exponent, containing the angle ϕ_2 between the particle 2 and the flow direction:

$$F(p_t, v, \phi_2) = \exp\left(\frac{vp_t \cos(\phi_2)}{\sqrt{1 - v^2} T_f}\right) \quad (5)$$

To get a feeling of the degree of collimation, let us estimate of the combination of parameters entering this exponent. We take $p_t \approx 2.25 GeV$ (the lowest p_t used by STAR in ridge studies to be discussed below) and $T_f \approx 100 MeV$. At the edge of the fireball $v \approx 0.7$ and thus a distribution $F \approx \exp(-11\phi_2^2)$ which is extremely well collimated, with a width much less than that of the observed “ridge”. At the opposite limit, at the center $r = 0$, there is no radial flow, $v = 0$, and ϕ_2 distribution is isotropic.

Thus the remaining task to be performed is the averaging over both the jet origination point r and the angle ϕ_1 , with the weights given by the distributions discussed above. Furthermore, the experimentally observable angle is neither ϕ_2 nor ϕ_1 but the angle $\phi = \phi_1 - \phi_2$ between particles 1 and 2, and so the correlation function is

$$C(p_t, \phi) = \quad (6)$$

$$\int P_{prod}(r) P_{quench}(r, \phi_1) F(p_t, v(r), \phi_1 - \phi) r dr d\phi_1$$

The only remaining input needed is the “Hubble law” for the radial flow, which we use in the form[7]

$$v(r) = r/(10 fm) \quad (7)$$

In Fig.2(a) we show the resulting angular distributions: the main result is that the peak survives the averaging. Furthermore, for small enough absorption lengths l_{abs} shown the result is remarkably independent on it: and

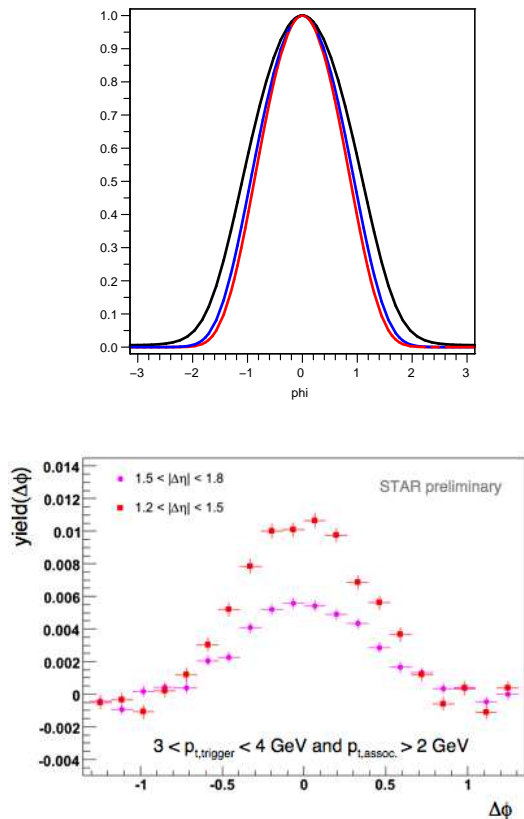


FIG. 2: (a) Calculated correlation function $C(p_t = 2.25 \text{ GeV}, \phi)$ as a function of the angle between two observed particles. Three curves (top to bottom) correspond to absorption length $l_{abs} = 1, 0.5, 0.25 \text{ fm}$. (b) Preliminary STAR data [4] on the “ridge” shape as a function of ϕ , with the jet component subtracted. AuAu at $\sqrt{s} = 200 \text{ GeV}$ and the central collision bin 0-10%.

since the absorption length is the only parameter of the model, and is believed to be rather small, we call the calculation “parameter free”. Still the reader should be warned that for weak quenching $l_{abs} > 3 \text{ fm}$ the width of the ϕ distribution grows catastrophically and the “ridge” correlation disappears.

While comparing these distribution to STAR data (Fig.2(b)) one finds that the model is *not* quantitatively accurate: the width we found is larger than the one observed. By making more complicated models for quenching one probably can recover better agreement: all we conclude for now is that the mechanism of “ridge” formation basically works.

III. OTHER OBSERVABLES

Spectra of particles belonging to a ridge are very different from those of the jet, being much softer.

As one can see from Fig. 3, they are much closer to the “bulk” represented by inclusive spectra. In fact they

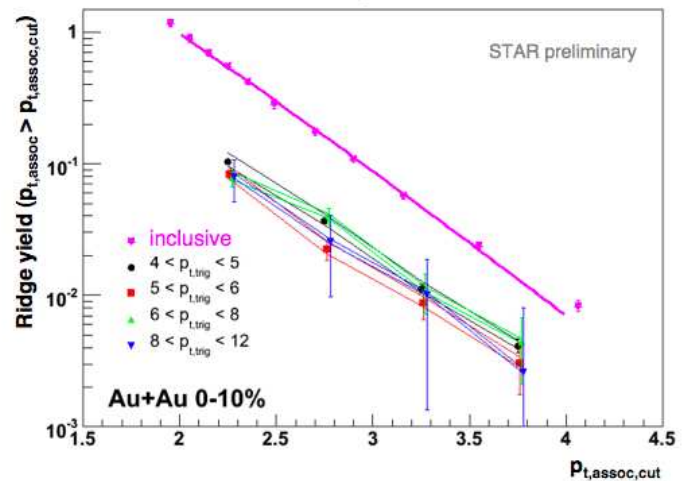


FIG. 3: Preliminary STAR data [4] on the spectra of the particles originating from a “ridge”, for different triggers. Triangles show spectrum of the “bulk” inclusive spectrum in the same momentum window.

have a bit stiffer slope, which is naturally explained by the fact that the distribution over their points of origin r discussed above is more biased toward the nuclear surface, than for the bulk matter.

Another important conclusion from Fig. 3 is that the spectra are completely independent on the jet momentum, which confirms that the “ridge” is not physically related to a jet itself. This fact is consistent with our model, since different jets have the same “collision scaling” distribution in the transverses plane.

Particle composition of the ridge particle is also very different from that of the jet. The fraction of baryons is much larger. This is naturally explained by the fact that the ridge is seen in the region of $p_t \sim 2 \text{ GeV}$ which constitute the tail of (boosted) Boltzmann distribution in which mass dependence is small. The same very phenomenon was observed in the bulk, and was explained by hydrodynamics [1]. Indeed, around $p_t \sim 2 \text{ GeV}$ the p/π^+ ratio crosses 1, and if the hydro-induced tail would dominate the spectrum at arbitrary large p_t (which it is not) the ratio would eventually be mass independent and reach 2, the number of spin components.

IV. OUTLOOK: 3-PARTICLE CORRELATIONS

The next step in data analysis is obviously adding one more particle correlated with the jet. Depending whether the second particle is included in the trigger condition or not, those can be called (2+1) or (1+2) correlations.

The latter case is basically the same as (1+1) in terms of geometry and trigger bias. In this case one would like to check whether the ridge extends longitudinally on both sides from a jet in each event. The alternative mechanism

suggested in [6] – a longitudinal extension of a jet due to *longitudinal* flow – can thus be finally confirmed or rejected. So far, the only observation *against* it is that the ridge was never seen near the away-side jet, which their model seem to predict to be even larger than the observed ridge at the trigger side.

The (2+1) case, with two hard particles in the trigger, is completely symmetric if two momenta are about the same, and therefore its trigger bias is completely different from the one discussed above. Indeed, it is determined by quenching along the sum of the paths of both jets

$$L + \bar{L} = 2\sqrt{R^2 - r^2 \sin^2(\phi_1)} \quad (8)$$

where \bar{L} is the path of companion jet shown in Fig.1 by the dashedline. Its exponent now favors the flow vector \vec{r} to be *orthogonal* to both jets, $\phi_1 = \pm\pi/2$. The favorite configurations is when two jets are emitted “tangentially” to flow: therefore we predict that now one should find the ridge at a completely different location! In rapidity it is expected to be symmetric around the di-jet center-of mass, the mean of the rapidities of both jets.

Summary

In short, the proposed mechanism works as follows. The “ridge” particles originate from glue radiated in the

hard collision along the beam direction, with calculated angular collimation coming from transverse radial flow. The most nontrivial point is the correlation between the direction of the flow and jet direction, which is induced by the jet quenching: as we show, it survives the averaging over positions and jet directions. We conclude that this mechanism is in good correspondence with many aspects of the data on the “ridge” phenomenon at hand. Further experimentation, especially with 3-particle correlations, will further elucidate whether this mechanism is indeed responsible for this phenomenon.

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- [1] D. Teaney, J. Lauret and E. V. Shuryak, Phys. Rev. Lett. **86**, 4783 (2001) [arXiv:nucl-th/0011058]. “A hydrodynamic description of heavy ion collisions at the SPS and RHIC,” arXiv:nucl-th/0110037. P. F. Kolb and U. W. Heinz, “Hydrodynamic description of ultrarelativistic heavy-ion collisions,” arXiv:nucl-th/0305084.
 - [2] J. Casalderrey-Solana, E. V. Shuryak and D. Teaney, J. Phys. Conf. Ser. **27**, 22 (2005) [Nucl. Phys. A **774**, 577 (2006)] [arXiv:hep-ph/0411315]. L. M. Satarov, H. Stoecker and I. N. Mishustin, Phys. Lett. B **627**, 64 (2005) [arXiv:hep-ph/0505245].
 - [3] J. Adams *et al.* [STAR Collaboration], J. Phys. G **32**, L37 (2006) [arXiv:nucl-ex/0509030].
 - [4] J.Putschke, Talk at Quark Matter 2006 (for STAR collaboration), Shanghai, Nov.2006.
 - [5] S. A. Voloshin, Phys. Lett. B **632**, 490 (2006) [arXiv:nucl-th/0312065].
 - [6] N. Armesto, C. A. Salgado and U. A. Wiedemann, Phys. Rev. Lett. **93**, 242301 (2004) [arXiv:hep-ph/0405301].
 - [7] This expression is supposed to give the final velocity which is obtained by the volume element which started hydro expansion at the point r . It should not be confused with a solution of hydro equations at some intermediate time moment.